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THE RADIATION AND LAG ERRORS OF THE TEMPERATURE ELEMENT OF GZZ-7 RADIOSONDE

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16. Abstract The radiation errors and lag coefficient of the thermistor temperature element used in a GZZ-7 radiosonde were tested using a wind tunnel. It was found that the heat dissipation from the ends of the thermistor could not be ignored. Based on the test data, an empirical formula about the relation between the dissipation coefficient of the thermistor and Reynolds number was obtained and the radiation and lag errors of the thermistor of the GZZ-7 radiosonde ascend- ing up to an altitude of 35 km were also calculated. It is shown that at a height of 30 km the solar radiation error is less than 1°C; in general the long- wave radiation error is less than -1°C; the time constant is about 10 seconds; and the maximum lag error is less than -0.4°C.			
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THE RADIATION AND LAG ERRORS OF THE TEMPERATURE ELEMENT OF GZZ-7 RADIOSONDE

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I. Foreword

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The model GZZ-7 radiosonde (hereinafter called model 7 for short) uses a cylindrical thermistor (0.47 mm in diameter and 10 mm long) as the temperature element; the thermistor was developed at the author's institute. The resistor surface is coated with a white layer [1]; the coating was also developed at the institute, with a solar reflectivity as high as 94 percent. When the coating was applied, the thermistor diameter increased by 1 mm. While sounding, the thermistor is at a considerable distance from the instrument package and is exposed completely in air flow; so as compared to the mechanical-change type radiosonde, there are relatively a smaller number of factors affecting thermometric precision. Thus, there are also fewer difficulties for arriving at a theoretical computational mode and for simulating measurement. In 1959, J. H. Shaw (United States) utilized the test results [2] of F. I. Badgley of Washington University on the lag coefficient to analyze and compute the radiation error [3] of model ML-419 thermistor elements (United States) in considerable detail. Yu. A. Glegolev [4] of the Soviet Union in 1965 and J. E. Talbat [5] of Australia in 1972 also conducted simple analyses for the theoretical computation of thermistor components used in their respective countries. However, by relying only on theoretical computation or simulation testing, it is still difficult to obtain a relatively reliable error. The paper introduces the key aspects for which this institute computed the radiation error and the lag error of a model 7 thermistor based on the laboratory measurements and testing of the lag coefficient and the radiation error; in addition, a comparison was made with the statistically analytical result of the day-and-night range data.

II. Formulas of Thermometric Error

* Numbers in the margin indicate pagination in the foreign text.

In making a comparison between the theoretical computation and laboratory measurements and testing, the author and his colleagues used a bronze filament (with a low coefficient of heat transfer), 4.5 cm long and 0.1 mm across, as the lead wire of the thermistor in order to fundamentally eliminate the heat-transfer error from the thermistor frame. The measuring power consumption is controlled to within 100 microwatts; thus, the error is less than 0.1°C. Moreover, at launching the model 7 radiosonde is 35 meters distant from the balloon, thus basically avoiding the balloon's effect on thermometry; hence, the paper will not discuss these errors.

If Q_1 stands for the solar short-wave radiation energy that the thermistor element absorbs per unit time; Q_2 and Q_3 represent, respectively, the absorbed and radiated long-wave radiation energy; and Q_4 represents the heat entrained from the air flow by the element. Then, according to the principle of energy equilibrium, we have

$$Q_1 - Q_2 - Q_3 - Q_4 = C \frac{dT}{dr} \quad (1)$$

In the equation, C is the heat capacity of the element; T is the temperature of the element; r is time; and $C(dT/dr)$ is the heat required for a temperature rise in the element. According to the heat dissipation rule of air flow, Q_4 is proportional to the temperature difference between the element and air flow, then

$$Q_4 = H(T - T_a) \quad (2)$$

In the equation, T_a is air-flow temperature; H is the coefficient of heat dissipation to the element by the air flow. Hence, the thermometric error of the thermistor is composed of the following parts:

$$T - T_a = \frac{Q_1}{H} + \frac{Q_2 - Q_3}{H} - \frac{C}{H} \frac{dT}{dr} \quad (3)$$

In the equation, Q_1/H is the solar short-wave radiation error; $(Q_2 - Q_3)/H$ is the long-wave radiation error; $(C/H)(dT/dr)$ is lag error of the element; C/H is the lag coefficient λ of the element.

These three errors are related to the heat dissipation coefficient H . As for the heat dissipation rule of a cylinder in an air flow, many researchers made

repeated measurements and tests, such as Hilpert [6], who derived the following dimensionless formula:

$$Nu = 0.43 + 0.48 Re^{0.5} \quad 1 < Re < 1000 \quad (4)$$

In the equation, Nu is the Nusselt number; Re is the Reynolds number with the respective definitions as the following:

$$Nu = \frac{Hd}{kS} \quad (5)$$

$$Re = \frac{\rho dW}{\mu} \quad (6)$$

In the equations, d and S are, respectively, the diameter and lateral area of the cylinder; k, ρ , μ and W are, respectively, the heat-transfer coefficient for air, density, coefficient of viscosity and flow rate. Assume that L is the length of cylinder, then $S = \pi dL$. Therefore, the heat dissipation coefficient of the lateral surface of the cylinder is given by the expression

$$H = \pi k L Nu \quad (7)$$

However, in the thermistor mode, length L is finite. As known from the next section for the result presented with laboratory measurements and testings, when one calculates the heat entrained by the air flow from the thermistor, the heat dissipated from lead wires at both resistor terminals cannot be neglected.

III. Experimental Measurements and Testing

1. Lag coefficient

The author and his colleagues used a closed-jet wind tunnel to determine the relationship between the lag coefficient and the Reynolds number by using the variable wind velocity method. The range of variable wind velocity is 0.12 to 2.6 meters per second; the simulated sounding altitude is close to 30 km. The horizontal installation of the thermistor under study is perpendicular to the air flow (refer to Fig. 1). The resistor is heated with an electric current to a temperature above 60°C; then, a resistance bridge and a timer are used to measure

the time required for a resistor to cool down to several temperature values. Thus, a cooling curve (It is a straight line on a monologarithm paper, referring to Fig. 2) is obtained. Then the value of λ (the time interval required for 63 percent change of the temperature difference) is calculated on Fig. 2. See details of the computation results as shown in Fig. 3.

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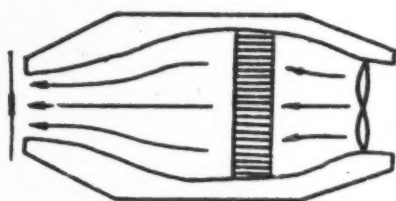


Fig. 1. Schematic diagram of wind tunnel testing.

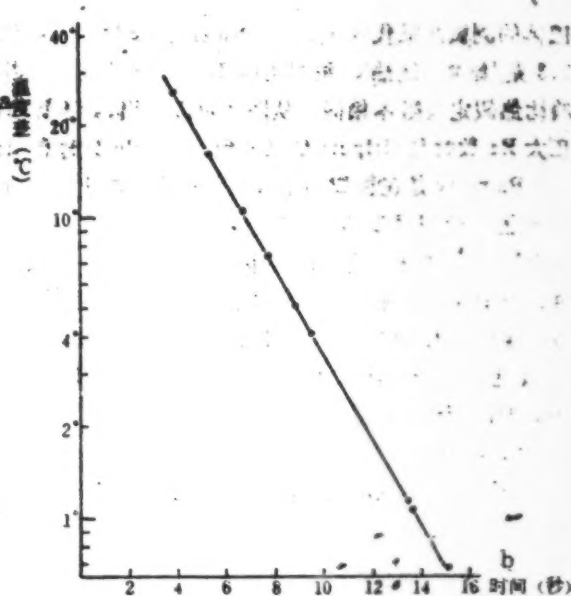


Fig. 2. Cooling line of thermistor. a - temperature difference (°C); b - time (seconds).

To examine how much the lead wires at both thermistor terminals are affected, the measurement results are compiled in the format of Nusselt (Nu) numbers. Since heat capacity is given by the expression:

$$C = c' \rho' \pi \frac{d'^2}{4} L + c'_1 \rho'_1 \pi \frac{(d_1^2 - d'^2)}{4} L \quad (8)$$

In the equation, c' , ρ' , d' and L are, respectively, the specific heat, density, diameter and length of the resistor; c'_1 and ρ'_1 are, respectively, the specific

heat and density of the coating layer. If heat dissipation of the lead wire can be neglected, then we obtain from Eqs. (7) and (8)

$$\lambda = \frac{C}{H} = \frac{c' \rho' d'' + c_1 \rho_1 (d^3 - d'')}{4 k Nu} \quad (9)$$

or

$$Nu = \frac{c' \rho' d'' + c_1 \rho_1 (d^3 - d'')}{4 k \lambda} \quad (10)$$

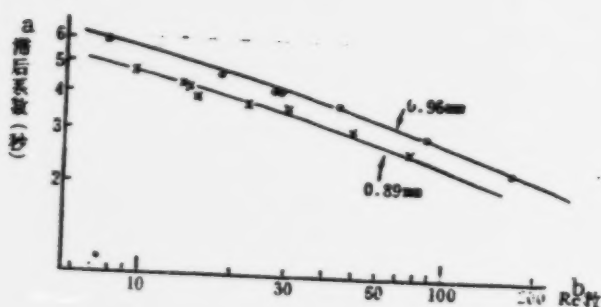


Fig. 3. Relation between Re number and lag coefficient of thermistor.
a - lag coefficient (seconds); b - Re number.

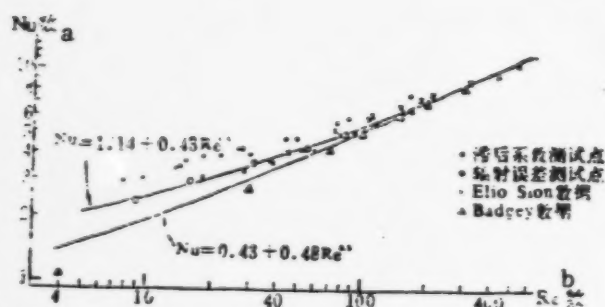


Fig. 4. Curve relating Re number and Nu number of thermistor.
• - lag coefficient measurement points;
• - radiation error measurement points;
x - Elio Sion data; Δ - Badgley data.
a - Nu number; b - Re number.

Insert the measured and test values for λ into Eq. (10), then we obtain the curve /4 (Fig. 4) relating Nu number with Re number. Densities of the resistor and the coating layer are, respectively, 4.8 and 2.3 grams per cubic centimeter. According to data extrapolation made by Backer [2] of United States, the specific heat c' is 660 milliwatts-second per gram-degree. It is assumed that the specific heat of the coating layer is the same as the resistor. From Fig. 4, it can be seen that the calculated Nusselt number from the measured λ is consistent with the Hilpert's results for high Re numbers; there is a significant difference for low Re numbers.

In a bell cover, Badgley determined the relation between λ and Re number by using a variable barometric pressure method. The range of pressure variation is 1035 to 19 millibars. Using a blower fan of a synchronous motor, wind speed was fixed at 3.05 meters per second. However, Elio Sion [7] determined the relation between λ , on the one hand, and pressure, temperature and wind speed, on the other by using the method of varying the barometric pressure, temperature and wind speed with an aneroid barometer. Using a rocker arm, Elio Sion obtained the relative wind velocity. Because of frozen lubricating oil, his experiment only could simulate up to an altitude of 300 millibars (-44°C); the range of wind speed variation is 15 to 1.5 meters per second. Both methods of heating the resistor and obtaining the value of λ from the cooling curve are the same as the method used by the author and his colleagues. By converting Badgley's and Elio Sion's measurement result into the form of Nu numbers before plotting in Fig. 4, we can see that Badgley's results are smaller than Hilpert's results at low Re numbers, while Elio Sion's results are larger than Hilpert's results, but smaller than the results determined by the author and his colleagues.

2. Radiation error

The above-mentioned small wind tunnel is still used for wind blowing; a 1,500 watt projection lamp is used for illumination to determine the curve (see Fig. 5) relating the Re number with the thermistor radiation error.

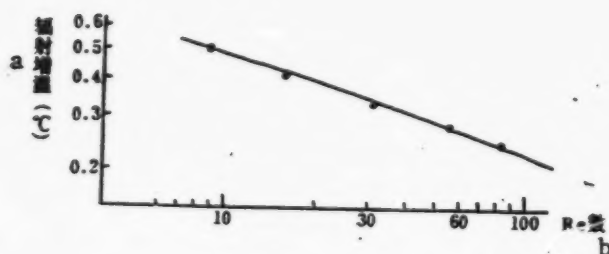


Fig. 5. Relation between Re number and radiation increase in thermistor temperature.
a - radiation increase in temperature ($^{\circ}\text{C}$);
b - Re number.

With perpendicular placement of light beam and thermistor, $Q_1 = a_s IdL$; a is the absorption coefficient for the light beam due to the coating layer; I is the intensity of light beam if the effect of lead wires at both terminals is neglected. Then the radiation error is

$$\frac{Q_1}{H} = \frac{a_s IdL}{\pi k L Nu} = \frac{a_s Id}{\pi k Nu} \quad (11)$$

or

$$Nu = \frac{a_1 Id}{\pi k(\Delta T)} \quad (12)$$

In the equation, $\Delta T = Q_1/H$ as the radiation increase of temperature is thus determined. The measurement and test data points are plotted in Fig. 4; we can see that the Nu numbers (obtained from measurement and testing results of radiation error) are still larger than the Hilpert's results, but still smaller than the Nu numbers obtained from the measurement and testing of the lag coefficient, though close to Elip Sion's results.

3. Analysis of measurement and test results: effect of lead wires

When one determines the lag coefficient the resistor temperature climbs above 60°C due to heating; the lead wire serves to dissipate heat from the resistor. When one determines the radiation error, the resistor and lead wire are heated by light beam simultaneously. Since the lead wire is more slender than the resistor and has a white coating layer, the radiation increase in temperature is smaller than for the resistor, thus also dissipating heat from the resistor. Compared to the situation when the lag coefficient was determined, the function of heat dissipation is smaller. Therefore, the calculated Nu number is greater than Hilpert's results, and smaller than the calculated Nu number based on the determined lag coefficient value. The thermistor (used in the United States) is much longer than the model 7 thermistor: it is 2.5 or 3.8 cm. The relative effect of the lead wires may be somewhat smaller, so the measurement and test results are closer to Hilpert's results.

Since the situation (while one measures and tests the radiation error) is closer to the real situation during a radiosonde launch, it is more rational to calculate the heat dissipation coefficient H from the Nu number found when determining the radiation error. The empirical formula is

$$Nu = 1.14 + 0.43 Re^{0.5} \quad (13)$$

This empirical formula is used in the following to calculate the radiation error and lag error.

IV. Calculation of Radiation Error

1. Solar short-wave radiation error

Assume that γ is the included angle between the resistor shaft and sunlight. During the ascent of the radiosonde, direct solar radiation absorbed by the thermistor is

$$W_d = a_s IdL \sin \gamma \quad (14)$$

During ascent of the radiosonde with a balloon, frequently the radiosonde rotates and swings ceaselessly along a helix; the relative orientation to sunlight of the resistor axis also ceaselessly varies. To seek a mean value, some researchers assume that the resistor is in horizontal constant-speed rotation. In this case, the absorbed mean direct radiation is

$$\overline{W_d} = a_s IdL \overline{\sin \gamma} \quad (15)$$

In the equation,

$$\overline{\sin \gamma} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \sqrt{1 - \cos^2 h \sin^2 \beta} d\beta \quad (16)$$

h is the solar angle; β is the orientation angle. When the solar angle is reduced from 90° to 0° , $\overline{\sin \gamma}$ decreases from 1 to 0.64. For ease in calculation, the following approximate formula can be used

$$\overline{\sin \gamma} = 0.64 + 0.004 h \quad (17)$$

Generally, the Earth-atmosphere system exhibits diffuse reflectivity with respect to reflection of sunlight. If we look only at the situation of altitudes above 20 kilometers, the reflected radiation absorbed by the thermistor is

$$W_r = \frac{\pi}{2} a_s dLIR \sinh \quad (18)$$

In the equation, R is reflectivity of the Earth-atmosphere system; the solar short-wave radiation error is

$$\frac{Q_1}{H} = \frac{\overline{W_d} + W_r}{H} = \frac{a_1 d}{\pi k} \cdot \frac{\left(0.64 + 0.004 h + \frac{\pi}{2} R \sinh\right)}{(1.14 + 0.43 R e^{0.5})} \quad (19)$$

from Eqs. (15), (17) and (18). Let 0.07 be the absorptivity of the coating layer; assume I to be 2 calories per square centimeter·minute; let d be 0.1 centimeter; and k and μ are the mean value at high altitudes. $k = 2.88 \times 10^{-3}$ calories per centimeter·minute·degree; $\mu = 0.87$ gram per meter·minute; and the unit of (ρW) is gram per square meter·minute. Then

$$\frac{Q_1}{H} = \frac{1.547 \left(0.64 + 0.004 h + \frac{\pi}{2} R \sinh\right)}{1.14 + 0.01458 (\rho W)^{0.5}} \quad (20)$$

When the solar angle, reflectivity of the Earth-atmosphere system, and the air flow quantity (ρW) are known quantities, the solar short-wave radiation error can be calculated. Table 1 lists the Q_1/H value of three occasions for calculating the mean atmospheric values at altitudes over the Beijing area; the ascent rate is assumed to be 7 meters per second.

Table 1. Solar short-wave radiation errors ($^{\circ}\text{C}$) of Beijing area.

高度 (公里)	I R = 70% h = 90°	II R = 35% h = 45°	III R = 10% h = 45°
20	0.82	0.47	0.26
25	1.08	0.52	0.48
30	1.25	0.78	0.63
35	1.63	0.94	0.72

* altitude (in kilometers).

From Table 1, we can see that the solar radiation error is less than 1°C at altitude of 30 kilometers in the usual situation (II). The error will exceed 1°C only when the solar angle is very high and a large area of congestus cumulus layer (I) appears.

2. Long-wave radiation error

Absorptivity of the white coating layer for long-wave radiation almost reaches 1; hence, the thermal radiation of the thermistor, and the absorption of long-wave radiation of the Earth-atmosphere system are relatively intense. Since the transmission problem of long-wave radiation of the Earth-atmosphere system is relatively complex, it is relatively difficult to precisely calculate the long-wave radiation error. When Shaw made his computations, he assumed that the Earth-atmosphere system below 20 km altitude is an unlimited large plane with the equivalent-effect temperature being T_b . Then the thermal radiation absorbed by the thermistor is /6

$$Q_2 = \frac{1}{2} a_b \sigma T_b^4 \quad (21)$$

In the equation, a_b is the absorption coefficient to long waves; σ is the Stefan-Boltzmann constant. The thermal radiation of the thermistor itself is

$$Q_3 = a_b \sigma T^4 \quad (22)$$

However, during Shaw's computations, his selected T_b values are not quite adaptable. In this paper, based on the equivalent temperature values of the Earth-atmosphere system thus determined in computing the long-wave radiation error, we have the three following altitude situations over the Beijing area:

- I: extensive and dense cloud layer is present in the troposphere, T_b at 223°K (10°C);
- II: average situation, T_b is assumed to be 254°K (-19°C); and
- III: troposphere is very dry and clean, and T_b is assumed to be 283°K (10°C).

From Eqs. (21) and (22), we can obtain

$$\frac{Q_2 - Q_3}{H} = \frac{a_b d \sigma \left(\frac{1}{2} T_b^4 - T^4 \right)}{k Nu} = \quad (23)$$

$$= \frac{2.87 \times 10^{-5} \left(\frac{1}{2} T_b^4 - T^4 \right)}{1.14 + 0.01458 (\rho W)^{0.5}} \quad (24)$$

In the equations, the unit of (ρW) is gram per square meter-minute. If the ascent rate is 7 meters per second, the long-wave radiation errors of the thermistor at altitudes over the Beijing area are listed in Table 2.

Table 2. Long-wave radiation error ($^{\circ}\text{C}$) of thermistor at altitudes over the Beijing area.

* 高 (公里)	I $T_1 = 223^{\circ}\text{K}$	II $T_1 = 254^{\circ}\text{K}$	III $T_1 = 283^{\circ}\text{K}$
20	-0.68	-0.07	0.75
25	-1.14	-0.33	0.74
30	-1.75	-0.74	0.60
35	-2.00	-1.47	0.15

* - altitude (in kilometers).

We can see generally the long-wave radiation errors are negative values, at -0.74°C at an altitude of 30 km. When an extensive cloud layer appears in the troposphere, the long-wave radiation error can exceed -1°C . However, when the troposphere is very dry and clean, the error may become a positive value, but less than 1°C . Since there is no sunlight at night, the error calculated from Eq. (24) is also the radiation error of the thermistor at night.

3. Radiation error in the daytime

In the daytime, there are the solar radiation error and also the long-wave radiation error.

$$\frac{Q_1 + Q_2 - Q_3}{H} = \left[1.547 \left(0.64 + 0.004 h + \frac{\pi}{2} R \sinh \right) + 2.87 \times 10^{-4} \left(\frac{1}{2} T_1^4 - T^4 \right) \right] + [1.14 + 0.01458 (\rho W)^{0.4}] \quad (25)$$

Table 3 lists the day-time radiation errors of the thermistor at altitudes over the Beijing area under three kinds of situations.

Under the general situation (II), we can see that basically the long- and short-wave radiation errors at 30-km altitude cancel out each other. However, at altitudes below 30 km, daytime radiation errors tend toward the positive side; at altitudes below 30 km, daytime radiation errors tend toward the negative

side. When the troposphere is very dry and clean, daytime radiation errors may very possibly exceed 1°C.

Table 3. Daytime radiation error (°C) of thermistor in Beijing

* 高 度 (公里)	I R=70% h=90° T _s =223°K	II R=35% h=45° T _s =254°K	III R=10% h=45° T _s =283°K
20	0.14	0.40	1.10
25	-0.06	0.29	1.22
30	-0.40	0.04	1.20
35	-1.06	-0.53	0.87

* - altitude (in kilometers).

4. Day-and-night range data of temperature data obtained by model 7 radiosonde

Liu Zongqing compiled statistics and analyses of temperature data [10] obtained by a model 7 radiosonde at 13.00 hours (solar angle about 40°) and 01.00 hour (at night) in the period between September and November in 1981 and 1982 at high altitudes over Beijing. Liu discovered that the mean diurnal temperature range did not exceed 1°C (Fig. 6) at altitudes below 15 millibars. Besides the solar radiation error, the diurnal range values also include the real daily variation in temperature of the atmosphere as such. From 01.00 to 13.00 hours, the daily variation of the atmosphere as such is estimated at about 0.5°C. It can be seen that the calculated results in this paper (curve 1 in Fig. 6) are relatively close to Liu Zongqing's results.

V. Computation of Lag Errors

The Nu number empirical formula (13) is substituted into Eq. (9); the lag coefficients can be computed.

$$\lambda = \frac{4.824}{k[1.14 + 0.01458(\rho W)^{0.5}]} \quad (26)$$

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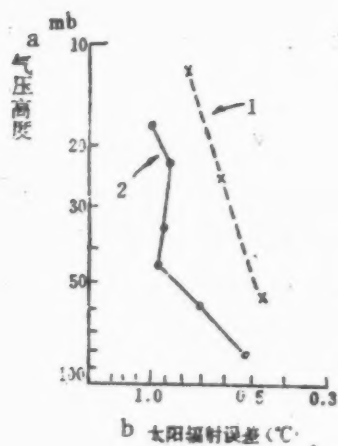


Fig. 6. Comparison between calculated value (1) and diurnal range statistical value (2) of solar radiation error.
a - altitude corresponding to the barometric pressures; b - solar radiation error ($^{\circ}\text{C}$).

In the equation, the unit of (ρW) is gram per square meter-minute, and the unit of k is milliwatt per centimeter-degree. The lag error can be computed using the following equation:

$$\lambda \frac{dT}{dr} = \lambda \frac{\Delta T}{\Delta Z} W \quad (27)$$

In the equation, $\Delta T/\Delta Z$ is the vertical temperature continuous decrease rate. Table 4 lists the lag coefficients and lag errors calculated according to the mean atmospheric and (possibly appearing) maximum continuous lapse rate over Beijing. The lapse rate for altitudes below 15 km is assumed to be -10°C per km. For altitudes over 15 km, the value is assumed to be 5°C per km, and the ascent rate at 420 meters per minute.

Table 4. Lag coefficient and (possibly appearing) maximum lag coefficient of model 7 radiosonde temperature element.

a 高度 (公里)	0	5	10	15	20	25	30	35
b 滞后系数 (秒)	1.7	2.3	3.3	4.6	6.3	8.0	9.8	11.6
c 滞后误差 ($^{\circ}\text{C}$)	0.12	0.16	0.23	0.32	-0.22	-0.28	-0.34	-0.41

a - altitude (in kilometers); b - lag coefficient (seconds); c - lag error ($^{\circ}\text{C}$).

We can see that the maximum lag error does not exceed $\pm 0.4^{\circ}\text{C}$ below 30 kilometers in altitude.

VI. Conclusion

There are very small radiation errors and lag errors as well as very high precision in temperature measurements for the ultrafine metal filament temperature element used in reference standard temperature radiosonde, but the temperature coefficient is very small (about 0.4 percent per °C) with complex and expensive remote sensing circuits, so the ultrafine metal filament elements are difficult to be widely accepted. The temperature coefficient of the thermistor is greater by one order of magnitude than that of the metal filament, therefore the thermistors are good for remote sensing and for wide-scale adoption. From the calculated results given herein, after high reflectivity coating layer is applied to relatively fine thermistor elements, the radiation error and lag error are relatively small; therefore, this temperature element is suitable to be employed in conventional radiosondes. However, relatively greater long-wave radiation errors may appear at night; this feature needs to be improved. If a computer is connected to the ground equipment for data processing, radiation and lag values can be refined using formulas derived in the paper, thus further enhancing temperature measuring precision at high altitudes.

· Lu Sumei, Wang Jiulian and Kou Hongwei did the measurement and testing work.

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